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The Second Year Laboratory

RADIOACTIVITY EXPERIMENT

The radioactivity sources used in this experiment emit beta and gamma rays at a safe level if handled properly. They should be treated with respect and kept away from the body. The alpha particles emitted by the Americium-241 sources do not escape from the source mountings. Care should be taken with both the radioactive sources and the lead absorbers to prevent any possibility of ingestion. The following instructions **must be followed:**

- **Do not** scratch the radioactive source surfaces.
- **Do not** release the Americium sources from their protective case.
- **Do not** leave sources in contact with your body for long periods.
- **Do not** remove the radioactive sources from the laboratory.
- **Do not** swallow a radioactive source.
- **Inform** a demonstrator immediately if a source breaks.
- **Do not** clear-up a broken source.
- **Always** return your sources to the box at the end of the session.
- **Do not** consume any food or drink in the laboratory.
- Mobile phones and ipods must be **switched off!**

Remember that you cannot see, smell, hear or feel radioactivity. Since radioactive sources cannot be switched off, you should always know their whereabouts, even while concentrating on something else!

Section 1 – Preliminaries (Pre-lab)

1.1 Objectives

- At the end of this experiment you should be able to:
  - Assess the safe handling of a radioactive source
  - Recognise different types of radioactive decay
  - Give examples of the random nature of radioactivity
  - Describe how the signal is generated in a silicon detector
  - Use a simple computer-aided data acquisition system
  - Describe the main interactions of electrons and photons
  - Identify the most likely interactions as a function of energy
  - Identify areal density as the main parameter of an absorber
- Other aims common to the whole 2nd Year Lab:
  - Plan an experimental measurement
  - Assign a meaningful uncertainty to an experimental measurement
  - Combine experimental errors using the error propagation formula
  - Keep an accurate record of your work
  - Write a scientific report which is well organised, concise, accurate and properly referenced
  - Explain and debate your work with others

1.2 Instructions

- You must complete each section and understand the physical processes involved before you continue to the next section. ***Talk to a demonstrator before you move on***. The more you talk to them, the easier you will find the work and the better you will do in your report.

- The time you should typically spend in each section is indicated, but this is only a rough guideline. It's preferable to complete fewer tasks well than to rush through the script.

- Before each experiment, spend a little time playing around to find the best way to set up the apparatus and take a few sample measurements before you proceed. Use your sample data to establish what columns your data table should have; how long you should measure for; and how many measurements you should make.

- Record all your findings directly in a lab book, not on a scrap of paper. This should include the data themselves, if not stored directly on the PC (make sure you regularly save it). Sketch the experimental layout and note the error associated with all measurements. Plot your results as you go along so that any problems in the data can be resolved while you have access to the apparatus. It is easier to tell from a graph than from a table of numbers whether your data are any good. Make sure you record in the lab book data tables, as well as graphs.

- Measurements are meaningless without errors: indicate error bars on all your graphs; always quote errors with your experimental results.

- Though the experiment is organised around a number of Tasks or Activities, it is the associated concepts and skills that are most important.

If you wish to discuss any issue related to this script or the Radioactivity experiment in general you should contact the Head of Experiment (details on the Radioactivity notice board).

1.3 Schedule

Below is a **rough** schedule for your progress through the experiment. This is **not** a strict timetable to follow but is intended to give you an idea of your progress. Each Section also details how long you should spend on each set of tasks. There is a lot of material in the lab so you must work efficiently to complete it – if you are struggling to complete the tasks reflect on whether you are collecting too much data, discuss the task with your peers or check your understanding of the task with a demonstrator.

Throughout the lab you will be recording comma-separated (CSV) data files. It is highly recommended that you create a Python or Excel template that will read in a CSV file and create a histogram of your data. This will allow you to easily plot your data as you go.

As always, if you have questions, please **ask a demonstrator!**

- Pre-lab: Complete Task 1 and attempt Task 2
- Session 1: Complete Section 2 and work through Section 3
- Session 2: Complete Section 3 and start Section 4
- Session 3: Complete Section 4 and start Section 5
- Session 4: Complete Section 5.1 and start Section 5.2
- Session 5: Continue through Section 5.2
- Session 6: Complete Section 5.2
- Session 7 and 8: Work on understanding your results from Section 5

1.4 Discussion sessions

We will hold discussion sessions:
1. In Term 1: Tues 3pm-4pm in Blackett 630.
2. In Term 2: Thur 4pm-5pm in Blackett 741.

The purpose of these sessions is to give you a chance to discuss the physics behind your experimental measurements with the Head or Deputy Head of experiment. It will also be used as a forum to discuss your results with others in your lab group but outside of your immediate lab partners.

These sessions are optional, though recommended. The demonstrators in the lab sessions will be focusing on the operational aspects of the experiment (i.e. making sure the equipment is working and you are collecting data successfully), rather than explaining the physics behind it. The discussion sessions will focus on this physics understanding.

Section 2 – Know Your Sources (Pre-lab)

Complete Task 1 and attempt Task 2 before start of lab cycle

(~1 hour)

Two questions must be considered before a radioactive source is chosen for a particular application: i) is it suitable for the task? and ii) is it safe to use? This section deals with these two issues. It will guide you to an informed decision as to the safety of the sources we use in the lab. It will also help you to characterise their properties in terms of type(s) of radiation emitted, its strength, energy spectrum, etc., so that you can interpret your experimental observations.

2.1 Radiation Units

The *activity* measures the strength of a source of ionising radiation. The SI unit of activity is the *becquerel* (Bq), which replaced the older *curie* (Ci): 1 Bq = 1 disintegration/second = 2.7×10^{-11} Ci.

The *absorbed dose* measures the total energy absorbed per unit mass. The SI unit of absorbed dose is the *gray* (Gy), although the *rad* is still used (but discouraged):1 Gy = 100 rad = 1 J/kg.

The *equivalent dose* measures the biological effect of the absorbed dose and is obtained by multiplying the latter by a quality factor, Q, which describes how much biological damage the specific type of radiation causes. Q = 1 for β and γ rays, but Q = 20 for α-particles. The *sievert* (Sv) is the SI unit of equivalent dose, replacing the *rem*: 1 Sv = 100 rem = Q x dose[Gy].

2.2 Radiation Exposure

Low-level radiation can be harmful to living tissue because it can directly (or indirectly) cause damage to important biological molecules, particularly DNA. Cells may repair themselves, in which case no ill-effects are observed. However, they may also die, exhibit impaired function (somatic effects), or be altered permanently in a way that is transmitted to later generations (genetic effects). These effects are probabilistic and depend on the accumulated dose, rather than the dose rate. Therefore, it is not possible to specify a totally safe level of radiation. This has two consequences. Firstly, a guide to acceptable levels can be obtained from a comparison with typical doses from the natural environment (Table I). Secondly, the **ALARP** principle (As Low As Reasonably Practical) should always be applied, for example, in the design and execution of this experiment.

Table I: Typical Radiation Dose Rates from Common Sources

Source	mSv/year
Cosmic rays	0.26
Natural backgrounds (U, Th, Ra)	1.65
Within body (^{40}K, ^{14}C)	0.30
Global fallout	<0.01
Nuclear power	<0.01
Single medical x-ray per year	0.37
Seven hours flying per year	0.05

Task-1: How safe is a typical laboratory beta source? (To be completed before lab cycle starts)
a) If you were to hold a 150 μCi source which emits β–rays, each of energy 2.8 MeV, enclosed in your hand for 5 minutes, what equivalent dose of radiation (in Sv) would you absorb? (Assume that your hand weighs 0.25 kg, has an area of 100 cm^2, and absorbs all the incident energy.)
b) Now repeat the calculation assuming that your hand is 1 m away from the radioactive source.
Hint: Work your way from the number of disintegrations per second in the source to the dose delivered to your hand – always use SI units. (1 eV = 1.6×10^{-19} J)

Note that Table I shows whole body doses (absorbed by each and every kg of the body), but the doses just calculated are concentrated into 0.25 kg. If the radiation were spread out over your whole body you would have to divide your result by your body mass in kg, instead of the 0.25 kg assumed for the hand, in order to make a fair comparison with Table I.2.8

Read and familiarise yourself with the Risk Assessment Form (at the end of the script), safe working practices on the front cover and the 'local rules' – a copy of which is available in the lab and a extract is at the end of the script.

⌛ The source in Task-1 is fairly representative of those used in this lab. You should now conclude about its safety in your lab book. ***You must discuss with a demonstrator your calculation & conclusion and demonstrate that you have read and understood the relevant safety material before handling any sources.*** You should have found that this experiment is perfectly safe, but that you should apply the ALARP principle and keep your distance from the source – even when you are 'not using' it!

2.3 The Sources

In this experiment you will use two radioactive sources: Strontium-90 (^{90}Sr or Sr-90) which emits electrons (β particles) and photons (γ-rays); and Americium-241 (^{241}Am, Am-241) from which we see only photons (it decays by emission of an α-particle followed by a γ-ray, but the α-particle does not escape from the protective brass casing around the source):

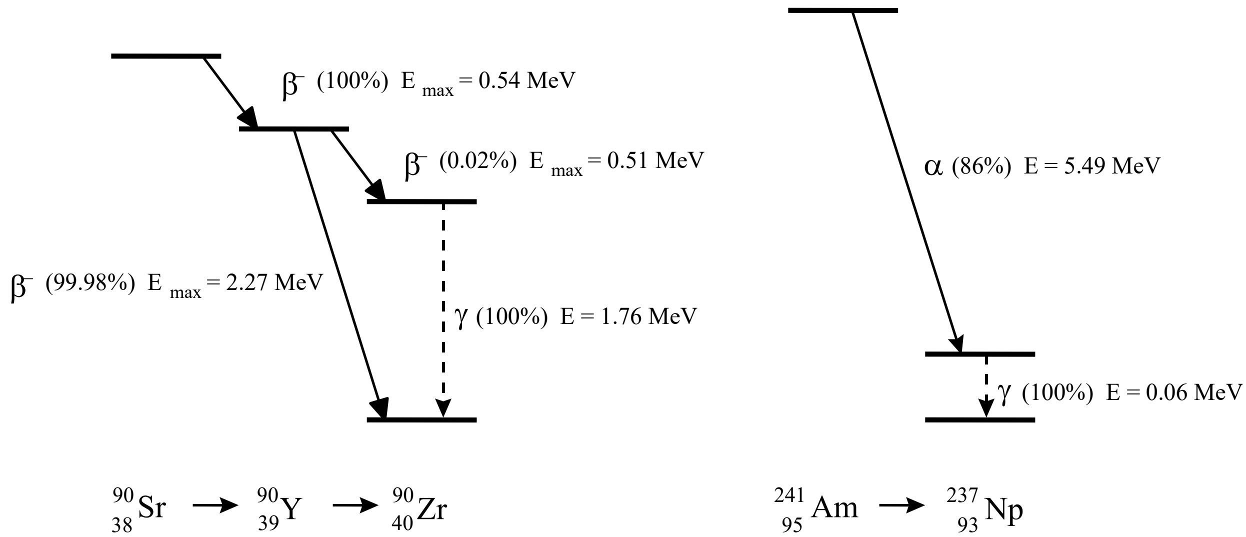

Figure 1: Decay schemes for Strontium-90 and Americium-241

The energies of the β decays in Figure 1 are labelled by E_{max}, which is the maximum energy possible for the β electron. A typical energy spectrum for these electrons is shown in Figure 2. Note also that there are several β decays going on in the Strontium source – and some high-energy γ-rays are also emitted! Most radioactive sources emit more than one type of radiation.

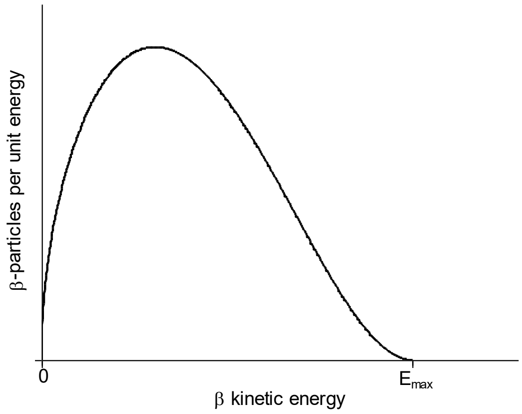

Figure 2: Typical energy spectrum of a beta emitter

Task-2: What is emitted by our sources?

a) Explain why β particles are <u>not</u> monoenergetic. *Hint: What is β decay? Compare with α decay. What particle was 'discovered' this way?*

b) Then explain why, on average, 50% of Strontium βs come from the Sr→Y transition and 50% from Y→Zr. (*Hint: The half life of Sr-90 is 28 years whilst that of Y-90 is only 64 hours.)*

c) Finally, sketch the overall energy spectrum describing all particles emitted by the Sr-90 source (β+γ), as well as the γ-rays emitted by the Am-241 source.

Section 3 – Basic Measurements

(Tasks 3 – 5: ~0.5 sessions),(Tasks 6 – 9: ~1 session)

3.1 The Experimental Set-up

A silicon detector detects radiation from a radioactive source. The output from the detector may be viewed on an oscilloscope, counted with a counter/timer, or fed into a computer. The image below shows a cartoon of the experimental equipment.

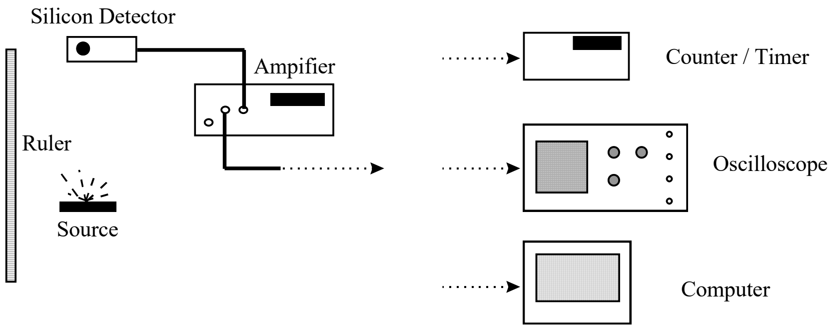

Figure 3: The experimental equipment.

3.2 The Silicon Detector

Charged particles are normally detected by the trail of ionisation they leave as they pass through materials. The ionisation is a result of the Coulomb interaction between the charged particles and the atomic electrons. Many types of detectors have been developed to record this trail of ionisation such as bubble-chambers, photographic emulsions, gas-filled chambers, and more recently, solid-state (i.e. semiconductor) devices such as the silicon detectors we will use here.

The ionisation produced by an incident charged particle must be drifted to an electrode where it is collected. Pure conductors cannot be used as detector material because fluctuations in the large steady state current would overwhelm the tiny current produced by the passage of a charged particle. The solution is to use semiconductors such as silicon that can be grown as a single crystal (so the energy bands extend over the entire volume) and sliced into wafers. The device used is called a *pn* junction, which you will hear more about in your solid state course.

For the purposes of this experiment you can treat the silicon detector as a 300 μm thick insulator across which a voltage of about 50 V is applied. This is sufficient to collect any ionisation (electron-hole pairs) in the detector within about 100 ns of its creation. The energy required to produce one electron-hole pair is about 3.6 eV and a relativistic electron going through the detector loses, on average, 27 keV for every 100 μm of path length in silicon.

The construction of the detector is shown in Figure 4. A 1 cm^2 silicon wafer is mounted on a ceramic support within a metal case. Bias voltage is supplied down the same cable that transfers the output signals to the computer. Note that the detector has a front (with the screws) and a back. The windows are covered with black tape to exclude light. The signal from the silicon is amplified and shaped by an integrated amplifier so that on the scope you see a smooth trace with an amplitude proportional to the total charge collected from the silicon, even though the charge carriers are not all collected at exactly the same time. The micro-controller applies a threshold to reduce noise and counts the number of pulses it receives from the amplifier that cross this threshold. Silicon detectors are delicate devices, please handle them gently. Each detector will also have slightly different gains and thresholds, since these depend on the various components of the amplifier circuit, which have some natural variation during production.

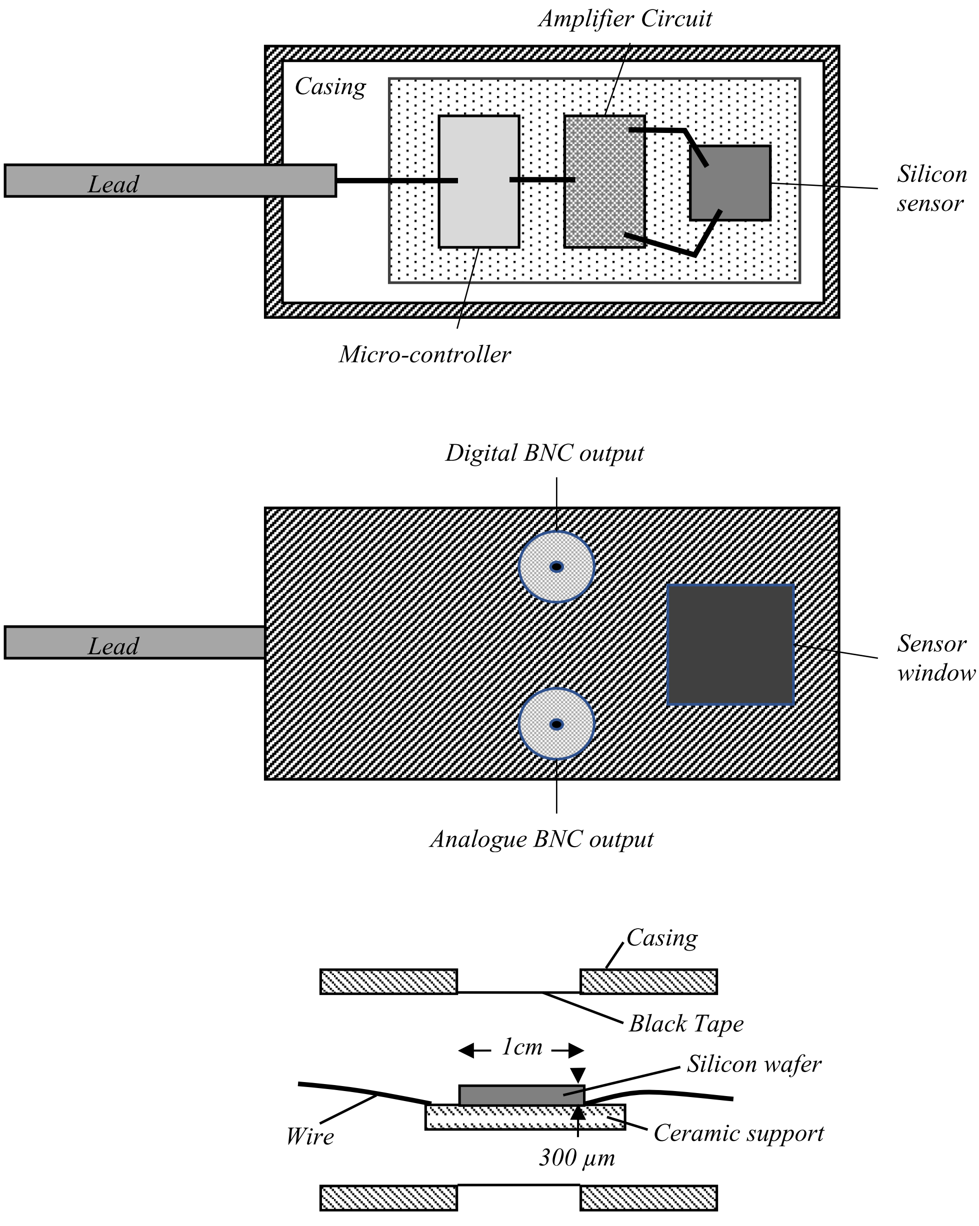

Figure 4: Construction of the silicon detectors.

3.3 The Data Acquisition (DAQ) Program

Run the *SimpleCounter.exe* executable. An error message may appear reading "Error - 1073807343" – click "Continue". This error arises because the program cannot find the detector through the default COM port. Click the drop-down box labelled *Detector Port* and select COM4 or COM5 (whichever is present). Now, click the "Run continuously" button (two white arrows on the top-left menu bar). The detector and DAQ are now ready to record data. The detector can produce test pulses at a rate of 2.5 kHz – click the *Test pulses* button to switch these on.

Task-3: Learn how to use the DAQ program
a) Switch the DAQ program to show the *Counter Plot* tab. This displays the number of counts measured by the detector within each cycle. The box on the top-right controls the number of cycles that will be recorded and the time per cycle (in seconds). Setup the DAQ program to take 10 cycles of 1 second each, then click *Start* button. The DAQ program will collect and plot data, then provide a window for you to save a text output file containing the number of counts in each cycle. **The output does not contain the time for each cycle, so make sure you note this carefully in your lab books!**
b) Switch to the *Interval Plot* tab. This displays the time between successive counts (the 'interval' between counts). The minimum interval detectable by the micro-controller can be set using the *Interval* control. The microcontroller can record minimum intervals of 31.25×2^n, for $0 < n < 8$, so the software chooses a value of n to produce an interval close to the value you put in the *Interval* box. Set the *Interval* to 1000ns. Set the *Integration time* to 1000ms – the detector will collect data for this length of time before plotting the results. Click the *Plot Interval* button to collect and plot the interval data for the test pulses – does this plot match what you expect?

3.4 The Strontium Source

Obtain a Strontium source and *note down* the number written on it. The source strengths differ so it is important that you retain the same one throughout the experiment.

Task-4: How does the ionisation detector respond to the Sr-90 source?
Switch on the apparatus and place the Sr source about 10 cm away from the detector window. Use the oscilloscope to view the analogue pulses – you will have to adjust the Y-axis to show ~200mV to find them. Sketch them in your lab book and explain all the features – think about which parameters you need to describe the waveforms and explain what causes them.

3.5 The Americium Source

Since there are only two of these sources you may have to come back to this part later.

Task-5: How does the ionisation detector respond to the Am-241 source?
Obtain an Americium source and place it on top of the detector. Sketch the pulses seen on the oscilloscope in your lab book and explain why they are different from those seen with the Strontium source.

3.6 The Simulation

We will use the GEANT4 software package to simulate the 2nd year lab radioactivity lab. It is used extensively in Nuclear physics, Medical physics, Space physics and High Energy physics – (almost) every experiment we run has been designed and optimised within a GEANT4 simulation.

GEANT4 allows users to simulate the components of an experiment in their correct physical location with respect to each other. Users can then generate particles within the simulated experiment with a given momentum and initial position. GEANT4 propagates these particles through the experiment and records the energy they deposit within each component.

GEANT4 is an example of a 'Monte Carlo' simulation – a simulation that uses random numbers to mimic an inherently random process. The software uses pseudo-random numbers to determine if and how particles interact with the experiment components. As such you should expect to see some variation in your results when repeating the same experimental setup, as you would in real-life.

3.7 Running the Simulation

For the first task using the simulation we want to run a simple example. The simulation is controlled by a 'macro' file – this is a list of GEANT4 commands in a text file that sets up the simulation geometry, determines whether we visualise the experiment, controls the source and detector positions and how many source decays we will simulate.

Task-6: Learn how to use the radioactivity lab simulation

a) Open a powershell: In the bottom left corner, click on the search icon and type 'powershell'. Click on "Windows Powershell" once it appears. Change into your home directory by typing:

cd "C:\Users\[your username]\OneDrive – Imperial College London\" <enter>

b) Make a directory to store your files in: **mkdir RadLab** and change into it: **cd RadLab**

c) copy the macro files needed for the simulation into your RadLab directory. The '.' at the end of the line forms part of the command. It's powershell shorthand for 'here'.
cp "C:\Geant4\Radioactivity_lab_simulation_files\macros*.mac" .

d) In your RadLab dir execute the simulation with the following command (both text strings on a single line). Note the ampersand, it will not work without it !
& "C:\Geant4\Radioactivity_lab_simulation_files-build\Release\lab.exe" "Example_Macro.mac"

e) Use the mouse and controls in the window that pops up to zoom in on the particles passing through the silicon detector.

f) Now, we want to create our own macro file. Make a copy of **Example_Macro.mac:**
cp Example_Macro.mac Example_Macro_Task6.mac

Now edit Example_Macro_Task6.mac with a text editor of your choice. Increase the number of decays in the /run/beamOn command to ~5000. Run this modified macro using (don't forget the '&'):
& "C:\Geant4\Radioactivity_lab_simulation_files-build\Release\lab.exe" "Example_Macro_Task6.mac"

g) The simulation will create a text file in the current working directory listing the energy deposited in the silicon detector by the particles that pass through it. Use this to create a histogram showing the energy deposited by the particles in the detector. Using the command `ls` should show you the file ('data_0.txt'). To check its contents quickly type: `cat data_0.txt` ('cat' is shorthand for 'concatenate')

Important! The text file will be overwritten if you run the simulation again – once you have run the simulation move and rename (`mv data_0.txt data_firsttry.txt`) the text file to tell you what you simulated. If the file is empty, try simulating more decays or moving the source closer to the detector.

3.8 An ideal electron source

Now we can use the simulation we are going to study the interaction of electrons with matter. We will make use of the one great benefits of simulations and choose to use an ideal electron source. This way we have full control of the electron energy, direction, and position.

Task-7: How does the ionisation detector respond to electrons?
a) Copy the
C:\Geant4\Radioactivity_lab_simulation_files\macros\Electron_Beam.mac
file to your home directory, read through the commands in the file then run it through the **lab.exe** simulation.
b) Zoom in on the silicon detector again – describe what the electrons are doing.
c) Repeat the above for electrons with an energy of 2MeV.
d) Make a plot comparing the energy deposited by the 2MeV and 300keV electrons.

3.9 An ideal photon source

Now we will use the same setup as before but study the interaction of photons. The Americium source emits mono-energetic photons with an energy of 60 keV, so the simulated ideal source is quite realistic in this case.

The GEANT4 simulation distinguishes between photons (low energy) and gamma rays (high energy). For the purpose of this study, you need to generate "gamma" particles with the specified energies.

Task-8: How does the ionisation detector respond to photons?
a) Repeat the studies in **Task 7** but this time edit the macro file to create a beam of gammas. Use the following two macro commands to only display photons that deposit energy in the silicon detector:

- */action/setStoreDetectedOnly*
- */vis/drawOnlyToBeKeptEvents*

Initially start with photons with an energy of 2MeV and try to find a photon interaction in the silicon using the visualiser. Once you are happy you understand these interactions repeat the study with photons from Am-241 – this can be approximated as an ideal photon source for photons with an energy of 60keV.

Hint: You will need to increase the number of particles simulated

Task-9: How do we calibrate our detectors?
a) Use the results of **Tasks 4 – 8** to establish a rough calibration of the oscilloscope pulse height, i.e. how many keV are deposited in the silicon detector for every 1 volt displayed on the scope. Do this for the oscilloscope pulses from both the Sr-90 and Am-241 sources.
Hint: Look at Appendices B and C!

Section 4 – Statistics of Radioactive Decay

(~0.5 sessions)

4.1 Counting Statistics

Radioactive decay is described by the laws of probability. If a radioactive source is put near a detector, a particular number of counts will be recorded in a given time interval. If the experiment is repeated, another number (generally different) will be recorded for an equal time interval. This indefiniteness in the number of counts comes from the random nature of the decay process. (Sometimes the random nature of the *detection* process must also be considered). A reminder of relevant statistical theory is found in Appendix A

Task-10: Counting statistics
a) For a single measurement yielding a number of counts *n,* the best estimate of the statistical error is $\sqrt{n}$. The statistical accuracy is *not* improved by splitting a long data collection time into several shorter ones. Show this by splitting one measurement over a 50s interval into 5 measurements each over a 10s interval.

b) Despite the above conclusion, it may be wise to perform any measurement twice or perhaps three times. Why?

The conclusions from **Task-10** should be taken into account when carrying out later experiments. It is also important to note that $\sqrt{n}$ gives the error in the *total count*, n, in a given time interval, Δt, and not the error in the count *rate.*

Task-11: Distribution of the number of counts for a small mean
Position the detector horizontally using the retort stand and clamp the source about 10cm above it, pointing downwards. Set the counter program to record a single 30s cycle, start recording, then add Al sheets to the detector to cut the count rate to 7–10 counts/s. Now change to *Counter Plot* mode and set the *Sample time* to 1s. Set up a 10-bin histogram with unity bin widths and acquire a large number of readings (~100). Compare your histogram with the theoretical Poisson distribution for the same mean, by plotting the theoretical values against your measured data (remember error bars!). Are your data consistent the Poisson distribution?
Hint: when are two measurements said to be consistent with each other?

Task-12: Distribution of the number of counts for a large mean
Remove some Al sheets to give a larger mean of ~100 counts per 1s interval. Histogram the distribution of counts and verify that, for this large value of the mean, a Poisson distribution has the form of a Gaussian distribution. A reasonable histogram may have 20 bins centred on the mean. Is this still consistent with a Poisson distribution?
Hint: When scaling the Gaussian to your data, ask yourself what is the integral of both distributions?

Task-13: Time-interval distribution
Adjust the number of Al sheets so that you get about 5000 counts/s. Set the program to *Interval Plot* mode, which measures the time elapsed between successive counts. The histogram now displays the number of occurrences with a particular time elapsed *between* counts. What *mean time* between counts do you expect? Taking this into account, set up and acquire the histogram (bin widths are in μs). You should find that there is a large variation around the mean time you predicted. Does this distribution have the shape you expect from Appendix A?

Task-14: What's happening at short time intervals?
Examine the shorter times in more detail using a smaller minimum interval (say 32.5ns). Explain what you see. Estimate the 'dead-time' of the detector.

⌛ Remember that the distribution of the number of counts in a fixed time should follow a Poisson distribution when the mean value is small and can be approximated by a Gaussian distribution when the mean is large (greater than ~20). This applies to many real-life counting experiments (not just radioactivity) so long as the probability of a 'count' is constant in time. The number of cars crossing a bridge in a fixed time, or the number of mutations in a DNA sequence after a certain amount of radiation can be Poisson processes (or Gaussian, if the mean is large). However, heavy traffic is neither – since the probability becomes time dependent!

Section 5: Experimental Investigations

(Tasks 15-17: ~1 session), (Tasks 18-20: ~2 sessions)

5.1 Count-Rate Variation with Distance

This part of the experiment investigates the variation in the intensity of the radiation with the distance *d* from the Sr-90 source. From **Task-1** you should understand the geometrical (solid-angle) effect which gives an inverse square law. Here, you will measure the counting rate at various distances and 'factor-out' the inverse square law by multiplying the counting rate $n/\Delta t$ by d^2 for each measurement. Any deviation in $(n/\Delta t)d^2$ from a constant will therefore have a physical origin which you should try to explain. Then you will calculate the source activity using the same data.

Clamp the source in the retort stand and centre it carefully touching the detector. Note the reading on the ruler of the alignment mark on the foot of the retort stand – your 'zero' separation. You can then slide the retort stand along the ruler to vary the source-detector distance out to ~1 m.

Task-15: Plan your measurements
Measuring a couple of data points at very different separations will give you a feel for how both $(n/\Delta t)d^2$ and its associated error vary with *d*. This will allow you to plan your measurement more effectively, plot your data sensibly and achieve reasonable errors for all values of *d*. Make a couple of trial measurements at different distances and calculate $(n/\Delta t)d^2$ and its error, using the formula below, for both instances. Express the error as a relative error i.e. (σ_u/u). What do you conclude from this about the counting interval at different distances?
Hint: If u = f(x, y) and the errors in x and y are independent, then the error in u is:

$$\sigma_u = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 \sigma_y^2}\ , \qquad (1)$$

where σ_x and σ_y are the absolute errors in x and y. You may assume that the error that there is no error in Δt i.e. your error expression should contain only 2 terms.

Task-16: Make your measurements
Measure, record and plot $(n/\Delta t)d^2$ against *d* for separations up to 1 m – plot the data as you take it! Choose the limits and regularity of your data-points in order to capture possible variations and trends. Based on **Task-15** you can adjust the measurement time at different distances such that the errors on each data point are comparable. In addition, recall the conclusions reached in **Task-10**.

Explain the deviations of your curve from that expected from the inverse square law.
Hint: There are at least two different effects.

Task-17: Source activity
Estimate the strength of the source in *becquerel*. You must include a justified error

What assumptions did you make in this estimate? Can you think why your activity may differ from the value considered in **Task-1**? ***As with all tasks, discuss with a demonstrator.***

5.2 Absorption Curves

In this section we will begin to understand the fundamental interactions between radiation and matter. From this point on we expect you to design your own experimental procedure – demonstrators will provide advice but will not tell you what to do! Plot your data as you go along and perform small test experiments to work out your optimal experiment design and data collection strategy.

Task-18: Absorption in aluminium – design your experiment
Read Appendix B to understand how electrons lose energy as they travel through matter. Design an experiment to measure the maximum energy of the electrons from the Sr-90 source. You should answer the following questions:
1) What quantity will you actually be recording? In Task 16 you recorded the count rate multiplied by the squared distance, for example, which you then used to calculate the source activity.
2) What do you expect to see when you plot your data and how will you use this to extract the maximum electron energy?
3) How many data points do you need to collect and what level of uncertainty is required?
4) How will you minimise potential systematic uncertainties in your result?

Task-19: Absorption in aluminium – perform your experiment
Collect data following the experimental procedure you designed in Task 18. How does your data compare to your expectation? Make sure you can explain your data and why it does (or doesn't) match your expectation.

Task-20: Range of electrons in aluminium and copper
Repeat Tasks 18 and 19, this time using copper rather than aluminium. Compare your results from the two metals (*Hint: Converting any thicknesses to areal density will make this easier)*. Is this what you expected?

⌛ Remember that β and γ-rays (and α-particles and neutrons) all interact in different ways. This needs to be taken into account when assessing the safety of radioactive sources and, more generally, the danger to people and the environment posed by their (mis-)use. However, it also makes them so useful in industry and in research!

Section 6: Further studies

(~2 sessions)

You should proceed to this section only if a demonstrator has examined your work and is satisfied that you have completed sections 2 to 5.

The goal of Section 6 is for you to work to better understand your results from Section 5. The following topics are suggestions for things that you could do, but the most important thing is to use this time to fully understand the results you have collected so far.

6.1 Comparing data and Monte Carlo simulations

In particle physics Monte Carlo simulation is used extensively to search for new particles or physics Beyond the Standard Model. We do this by comparing our data to our simulation, with the simulation including all of our known physics. Whilst there is little chance of us discovering new physics in an undergraduate lab, we can use our simulation to understand our lab experiments more completely.

The example below performs a Monte Carlo simulation of the ND-squared experiment from Task 16. You can easily alter the simulation macro to replicate a different task in the lab script. Alternatively you could use the ideal photon and electron source scripts to better understand the data you have collected.

Replicating the ND-squared experiment using the Monte Carlo simulation
Your aim here is to use the Monte Carlo simulation to mock-up the data collected in **Task-16.**
a) Copy the ND2 macro to your home directory and edit it match the data you collected.
"C:\Geant4\Radioactivity_lab_simulation_files\macros\NDSquared_Example.mac"
b) Run some test simulations to understand how many events you need to simulate at each distance – do not attempt to simulate separations greater than ~40cm, since this will take too long.
*Hint: use the '-b' option **(lab.exe -b NDSquared_Example.mac)** to switch off the visualiser. As a guide the macro above will take about 1 hour to run.*
c) Collect your simulation data and produce an nd^2 plot. Compare this to your data from **Task-16**. Identify regions that agree or disagree and discuss possible reasons for this.
Hint: You must carefully re-normalise your simulation to make sure you are comparing like with like
d) Try to get your simulated data to match the real data. You can try varying the detector deadtime, adding very thin sheets of aluminium to simulate additional shielding, altering the vertical position or rotation of the source etc.
e) From your tuned simulation calculate the activity of the real lab source and compare to your result from **Task-17**.

6.2 Estimating systematic uncertainties

Every experiment will have some associated uncertainties. These can be random fluctuations, constant systematic effects, varying systematic effects or just plain mistakes in the data collection or analysis. Understanding this "systematic uncertainties" is perhaps the most important work we perform as scientists.

Use the experimental equipment or simulation to understand the effect of potential systematic uncertainties on your results.
Consider the data you have collected and whether you can explain the features of each plot – are neighbouring measurements consistent with your expectation? Each data point you collect should have an associated systematic uncertainty. Ideally these systematic errors should be measured directly, otherwise they can be calculated using reasonable assumptions. For each experiment think of the different factors that could affect your data, rank them in importance, then try to come up with a method to measure them.

Appendix A – THE STATISTICS OF COUNTING

A.1 Poisson distribution

For times very short compared with the mean lifetime, the number of decays from a radioactive source in a given time will follow a Poisson distribution (because the decays are independent of each other). If, after many trials, the mean number of counts in a time interval Δt is found to be m (not necessarily integral) then the probability of obtaining a value n (necessarily integral) in a single measurement is:

$$P(n) = \frac{m^{+n} e^{-m}}{n!} \quad \text{(A1)}$$

The standard deviation, σ, is given by:

$$\sigma = \sqrt{m}\ . \quad \text{(A2)}$$

A.2 Gaussian distribution

When m is large, the Poisson distribution is very similar to the Gaussian distribution (and much easier to calculate…). The Gaussian *probability density* $P(x)$, such that $P(x)dx$ is the probability for an outcome between x and $x+dx$, is given by:

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-m)^2}{2\sigma^2} \right]. \quad \text{(A3)}$$

A.3 Time interval distribution

The probability, dP_t, that there will be (i) an event in a time interval dt and (ii) no event during the preceding elapsed time t, is the product of the individual probabilities (i) and (ii). If m is the mean number of counts per second, then mdt is the probability of there being a count in time interval dt. The probability for no events during the preceding time t when mt events could be expected is:

$$P_0 = \frac{(mt)^0}{0!} e^{-mt} = e^{-mt}\ . \quad \text{(A4)}$$

The combined probability is therefore:

$$dP_t = m\, \mathrm{e}^{-mt}\, dt\ , \quad \text{(A5)}$$

so the time interval distribution is exponential – i.e. the *smaller* the elapsed time, t, is, the *higher* is the probability that an event will *not* occur during the elapsed time t, and then *does* occur in the subsequent time interval dt. The histogram of the time interval distribution that you will look at using the computer involves an integration of this probability distribution over the histogram bin width Δt. The probability of having an entry in the bin from t to $t + \Delta t$ is:

$$\int_t^{t+\Delta t} dP_t = \int_t^{t+\Delta t} me^{-mt} dt = \left[-e^{-mt}\right]_t^{t+\Delta t} = \left(1-e^{-m\Delta t}\right)e^{-mt} = Ce^{-mt}\ , \quad \text{(A6)}$$

so the histogram distribution is also expected to be exponential. Note that if the detector has a dead-time t_D, this essentially results in the loss of any counts between time 0 and t_D. The overall fraction of counts *lost* is therefore:

$$1 - e^{-mt_D}\ . \quad \text{(A7)}$$

Appendix B – INTERACTION OF ELECTRONS WITH MATTER

Electrons penetrating matter with energies in the range created by radioactive β-emitters (10 keV to 10 MeV) lose energy due to inelastic collisions with the atomic electrons and are deflected almost entirely due to elastic collisions with the atomic nuclei. The result of this is a gradual decrease in the energy of the electrons as atoms are excited or ionised along the path, and repeated deflections of the incident electrons due to the elastic collisions with the nuclei. Energy loss due to Bremsstrahlung radiation in the Coulomb field of the nuclei is not an important mechanism of energy loss at these relatively low energies, though there is some contribution in the case of lead.

B.1 Energy loss due to inelastic collisions

The interaction of the incident electrons with the atomic electrons is characterised by the fact that the energy transferred to the atoms per collision is very small. Even for very high primary energies atomic *excitation* is more probable than *ionisation*. Even when ionisation does occur, the resulting secondary electrons have a mean kinetic energy of only a few eV. The total energy loss after passage through a foil of thickness x is therefore the result of a very large number of small energy losses. The theory was developed mainly by Bohr, Bethe and Bloch and can give a very accurate description of the phenomena. For relatively small energies, the mean rate of energy loss with distance can be written approximately as:

$$\frac{\overline{dE}}{dx} = \frac{4\pi e^4 NZ}{mv^2} ln\left(\frac{1.16E}{I}\right) = 0.306\rho\frac{Z}{A}\beta^{-2} ln\left(\frac{1.16E}{I}\right)\ [MeV/cm] \qquad \text{(B1)}$$

where N is the number of atoms per cm^3, v is the electron velocity, I is the mean excitation energy of the atomic electrons, ρ is the density, A is the atomic weight, and $\beta = v/c$. Note the units of I.

Table B1: Properties of materials

		H	C	Al	Fe	Cu	Sn	W	Pb	U
Z		1	6	13	26	29	50	74	82	92
A		1.0	12.0	27.0	55.9	63.5	118.7	183.9	207.2	238.0
ρ	g/cm^3	0.07	2.27	2.70	7.87	8.96	7.31	19.30	11.35	18.95
I	eV	15.6	76.4	150	243	279	472	680	737	853

Apart from the Z/A factor, which itself is approximately constant, dE/dx is approximately proportional to the density of the matter that is penetrated. A very slight dependence on Z occurs through the excitation energy appearing in the logarithm. Some experimental values of I are given in Table B1. The mean rate of energy loss with areal density (ρx), $dE/d\sigma$, calculated for Aluminium and Lead using these data is shown in Figure B1. The energy loss at first falls sharply with increasing energy, reaches a minimum when $E \sim 1$ MeV, and then increases very slowly, logarithmically.

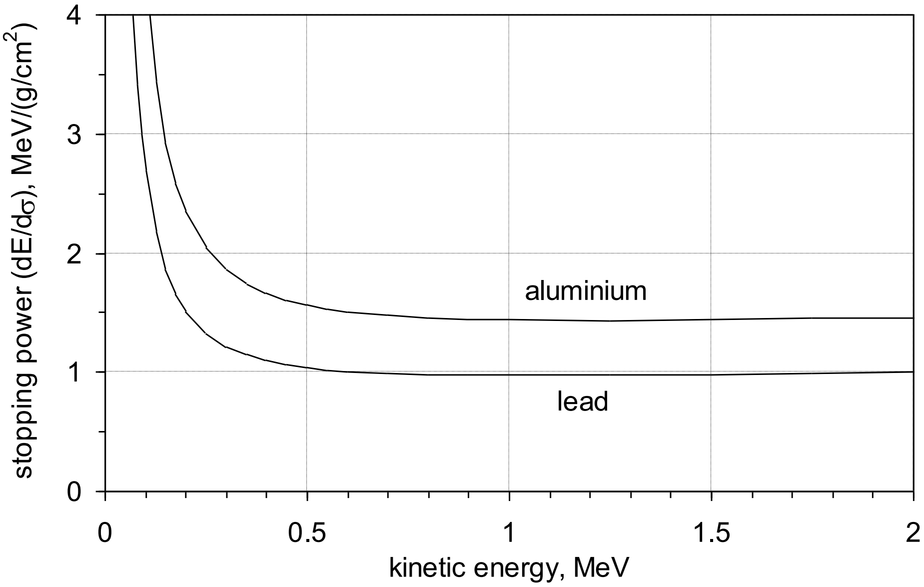

Figure B1: Mean energy loss for aluminium and lead foils of the same areal density.

B.2 Absorption of β rays

β-rays (electrons) will eventually be absorbed if they lose all their energy in matter. The number of electrons registered across an absorber decreases initially very rapidly with increasing thickness since the lower energy electrons quickly lose all their energy. As the thickness increases further, the number of electrons slowly approaches the background intensity, which can be dominated by a γ-component emitted from the same source. The maximum energy E_{max} of the β-spectrum can be determined from the range R of the electrons. Their relationship can be parameterized by:

$$R = 0.11\left(\sqrt{1+22.4E_{\max}^2}-1\right), \quad 0 < \mathrm{E}_{\max} < 3\,\mathrm{MeV} \tag{B2}$$

where E_{max} is in MeV and R is in g/cm^2.

B.3 Elastic scattering

Electrons passing through matter are scattered by the atomic nuclei. If the thickness of material d is very small ($d \ll 1/\sigma N$, where σ is the cross-section and N the number of scattering nuclei per unit volume) there is essentially only single scattering. For thicker materials, multiple scattering is seen, in which case the probability that a given scattering angle is due to a number of successive single scatters becomes appreciable. The angular distribution, $W(\theta)$, of the scattered electrons is approximately Gaussian as long as the mean scattering angle is below 20°, whilst for larger thickness the angular distribution has the form $W(\theta) \sim \cos^2\theta$. The mean scattering angle attains its maximum value ($\theta_{max} \approx 33°$) and remains constant when the thickness increases still further.

B.4 Electron backscattering

Electrons incident on a foil of material can be deflected in the backward direction by single or multiple scattering off the atomic nuclei. The number of backscattered electrons increases as the thickness of material increases until reaching a saturation value for a definite thickness – the 'thickness for saturation backscattering'. This thickness depends on the range of electrons and the atomic number, Z, of the material.

Appendix C – INTERACTION OF γ-RAYS WITH MATTER

Since γ-rays are uncharged, unlike electrons, there is no direct, continual energy loss by ionisation when they pass through matter; they either interact in some way or they continue undisturbed. Let N be the number of photons which pass through a thickness x of material, with N_0 incident (see Figure C1). The number of photons that interact in an additional thickness dx is -dN. We can write:

$$dN = -\mu N dx\,, \tag{C1}$$

where μ is a constant depending on the energy of the γ-ray and the material of the absorber and is called the 'photon attenuation coefficient'. Rearranging this equation and integrating, we have:

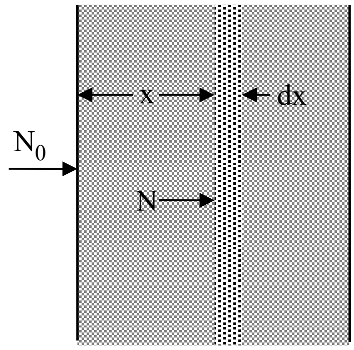

Figure C1: Photon absorption

$$\int_{N_0}^{N} \frac{dN}{N} = -\mu \int_0^x dx\,, \quad \text{or} \quad ln\left(\frac{N}{N_0}\right) = -\mu x \tag{C3}$$

giving

$$N = N_0 e^{-\mu x}.$$

The fraction of the original γ-rays that survive unchanged falls exponentially with distance x. It is this property that accounts for the fact that photons do not have a well-defined 'range' in matter.

There are three main processes whereby γ-rays interact with matter: the photoelectric effect, Compton scattering and pair production. In the photoelectric effect, all the photon energy goes into the photoelectron and the absorbing atom and is rapidly converted into ionisation – as seen with the Am-241 γ-rays. In pair production, the energy goes to create an electron-positron pair. This process dominates at the highest energies but at our energies is small or zero. The Compton effect describes the scattering of photons from electrons and is of particular importance around 1 MeV and so is of particular relevance to the Strontium source (see Figure C2).

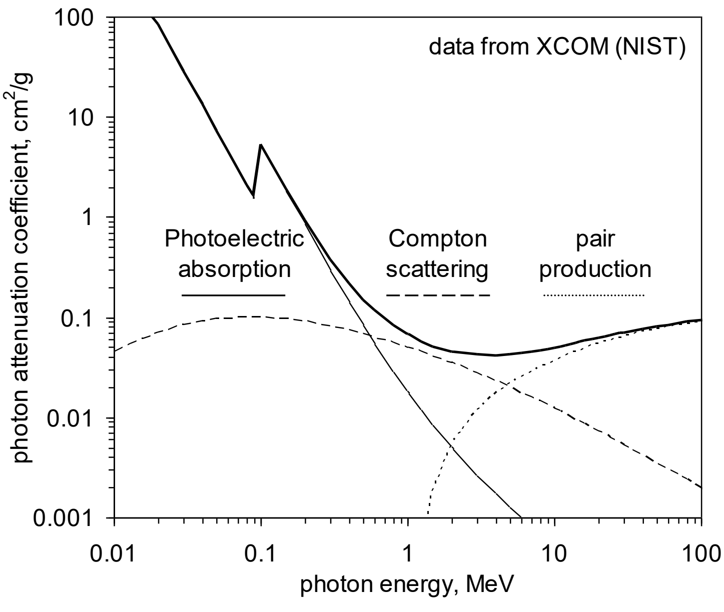

Figure C2: Photon attenuation in lead

The dominance of Compton scattering leads to a complication. The scattered photons, though of lower energy, will come off over a wide range of angles and, depending on the geometry of the source, absorber and detector, may still be counted. The overall attenuation with thickness will still however be close to exponential, particularly at the larger distances.

Appendix D – The Data Acquisition System

For some experiments it is useful to be able to rapidly record large numbers of readings and this task is easily performed using a PC, with a suitable Data Acquisition (DAQ) board inserted in one of the expansion slots or (in this case) built in to the detector. This board features analogue-to-digital (ADC) and digital-to-analogue conversion, as well as clock-generation, timing control and general-purpose digital input/output.

The LabVIEW software package allows "Virtual Instruments" to be set up, with all the control and indicator functions of 'real' devices, using a library of software functions to control the hardware. The programme 'language' is based on a visual representation of how the various parts of the system are connected, i.e. 'wired up' and how the data flows from one element to the next.

TO SWITCH ON:
Make sure that the main power switch at the socket and the PC are ON. When the PC is powered up, run the *SimpleCounter* executable. It will automatically present the user with the control panel for the Rad Counter device, which consists of a set of switches, input fields, buttons and displays, like the controls of a real counter unit. These controls are operated with the mouse, just point the cursor and click… you will soon get the idea or ask a demonstrator. When starting the program an error message may appear reading "Error -1073807343". This error arises because the program cannot find the detector through the default COM port. Click the "Continue" button then use the drop-down box labelled *Detector Port* to select the listed COM port (usually COM4 or COM5, not COM3)

When the selected parameters have been set up, then the programme is started by 'clicking' on the circling arrows in the top control bar second from the left. The arrow changes to a moving arrow, indicating that the code is running, and a new icon appears in the position third from the left. Clicking here will abort the run, if you have made some error. **Note that the selected values for the controls are only registered when the code is started; changing values during running will have no immediate effect.** Two 'modes' of operation have been coded:

- In **Counter** mode the number of input pulses above the threshold in the interval of time selected by the *Sample Time* box at the upper-right is recorded. This is repeated for the number of cycles set in the *Number of cycles* box. Whilst collecting data the *Counter Plot* histogram will update showing the number of counts for each cycle and the *Rate* meter will show the current event rate in Hz.
- In **Interval** mode the time between two successive input pulses above threshold is measured (μs). Switch the tab to the *Interval Plot*. The minimum interval detectable by the micro-controller can be set using the *Interval* control. This minimum interval is 31.25×2^n, for $0 < n < 8$. The maximum interval is set automatically by the micro-controller and is limited to 500 times the smallest interval. The *Integration time* (ms) input controls how long the detector collects data for before plotting it. Click the *Plot Interval* button to collect and then plot the interval data. Nothing will happen until the *Integration time* has passed.

The result of most of these operations is a histogram of values (counts/microseconds) which is presented at the end of the run. It is important that the histogram parameters are set properly before any long data-taking run is started. Check with short runs first! The mean and R.M.S. deviation of all the values is also calculated. **To export data, simply right-click on the histogram and select export. Record the histogram settings in your lab books.**

Appendix E – Useful links and references

Some further reading

– A good introduction to radiation detection, at the level of the Radioactivity experiment:
W. R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, Springer-Verlag

– A more comprehensive textbook on radiation detection, widely used by experimental physicists:
G. F. Knoll, *Radiation Detection and Measurement*, Wiley

– A good introduction to the statistics and errors in physics measurements
P. R. Bevington & D. K. Robinson, *Data Reduction and Error Analysis for the Physical Sciences*, McGraw-Hill

– Good introduction to nuclear physics with a lot of material on radioactivity
K. S. Krane, *Introductory Nuclear Physics*, Wiley.

Useful reference databases on the Web

Radiation Protection
http://www.hpa.org.uk/radiation/ UK Health Protection Agency
http://www.irpa.net/ International Radiation Protection Association
http://www.radiation.org.uk/ Links to Radiation Safety Websites

General Atomic Physics Resources
http://physics.nist.gov/PhysRefData/ National Institute of Standards and Technology (NIST)

Stopping Power and Ranges for Electrons, Protons and Alphas
http://physics.nist.gov/PhysRefData/Star/Text/contents.html *estar, pstar, astar* (NIST)

Photon Cross Sections
http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html XCOM (NIST)

Tables of Radioactive Isotopes
http://ie.lbl.gov/toi/ LBNL Isotopes Project – LUNDS Universitet
http://atom.kaeri.re.kr/index.html Korea Atomic Energy Research Institute

General Nuclear Physics Resources
http://t2.lanl.gov/ T-2 Nuclear Information Service (Los Alamos National Laboratory)
http://www.nndc.bnl.gov/ National Nuclear Data Centre (Brookhaven National Laboratory)
http://www.nea.fr/html/dbdata/ Nuclear Energy Agency (OECD)

Other databases
http://www.webelements.com/ Periodic Table (WebElements™)
http://www.matweb.com/ Material Property Data (MatWeb™)
http://physics.nist.gov/cuu/Constants/index.html Physics Constants (NIST)

Appendix G – Radioactivity Report

The two-page report should be written using the template indicated by Prof. Colling in his introduction to 2nd Yr Lab. The report should be based around one particular topic and cover the method, results, and conclusions of your studies. Some suggestions are given below, but you may agree another with your demonstrator:

- The interaction of photons (different materials, energies, etc)
- The interaction of electrons (different materials, energies, etc)
- Comparison of the interactions of photons and electrons
- The nd^2 plot (leading to the activity of the source)
- The absorption plots (leading, at least, to the areal density)

You are expected to show *knowledge* and *insight* into your chosen topic – going beyond mere exposition of work methods and raw facts: you should demonstrate *critical thinking* and *argue* your conclusions, communicating these in a concise but accurate way.

Finally, remember that you have plenty of *literature* at your disposal that can help you argue your case. Do not quote *verbatim* from sources but cite them in your 'References' section if you use the information. Beware of web pages, especially personal ones: they may not apply to your particular case and are often incorrect. You cannot blame an incorrect source – only yourself for using it!

[**Important reminder:** As you go along, make sure that for each task requiring a numerical result you have given a value, an error and an interpretation. For example, you measured the source activity to be XX±YY Bq and, in your opinion, this value makes sense because…. This will be assessed. **Make sure you've discussed all conclusions with a demonstrator**.]

Appendix F: Risk Assessment & Standard Operating Procedure

1. PERSON(S) CARRYING OUT THIS ASSESSMENT – This assessment has been carried out by the head of experiment.	
Name (Head of Experiment)	Mitesh Patel
Date	30/09/2025

2. PROJECT DETAILS.						
Project Name	Radioactivity Experiment				Experiment Code	
Brief Description of Project Outline	2nd Year Lab Radioactivity Experiment					
Location	Campus	South Ken	Building	Blackett	Room	407

3. HAZARD SUMMARY – Think carefully about all aspects of the experiment and what the work could entail. Write down any potential hazards you can think of under each section – this will aid you in the next section. If a hazard does not apply then leave blank.			
Manual Handling		Electrical	Various pieces of electrical equipment.
Mechanical		Hazardous Substances	Radioactive sources.
Lasers		Noise	
Extreme Temperature		Pressure/Steam	
Trip Hazards	Bags/Lab stools	Working At Height	
Falling Objects		Accessibility	Limited space between some benches / sets of equipment.
Other	No eating / drinking in lab.		

4. CONTROLS – List the multiple procedures which may be carried out during the experiment along with the controls/ precautions that you will use to minimise any risks. Remember to take into consideration who may be harmed and how – other people such as students, support staff, cleaners etc will be walking past the experimental setup even when you aren't around.	
Brief description of the procedure and the associated hazards	**Controls to reduce the risk as much as possible**

Electrical:	Equipment is mains powered. No adjustments to be made by students
Hazardous substances:	Radioactive sources: Am241, Sr90. Should be handled with care. No tampering with protective cases and surfaces. Sources must be signed-in/out and remain in 407 in designated area. ALARP principle to be followed at all times. Acrylic shielding should be present between setups while sources are in use. Sources should be replaced in lab safe while not in immediate use. Follow instructions in script.
Accessibility/ Trip Hazards:	All bags /coats to be kept out of aisles and walkways.
Other:	No eating or drinking in lab.

5. EMERGENCY ACTIONS – What to do in case of an emergency, for example, chemical spillages, pressure build up in a system, overheating in a system etc. Think ahead about what should be done in the worst case scenario.
All present must be aware of available escape routes and follow instructions in event of an evacuation. If a source drops and breaks, students should move away, and inform a demonstrator or the RPS (Jayesh Hirani) immediately.

Extract from Local Rules: Summary of Working Instructions (Standard Operating Procedures).

1. Make sure you have read and understood these local rules.
2. Sign the list of authorised users. [Effectively done by the demonstrator discussing Task 1 with you and signing your book.]
3. Sign for and note the time of issue and return of sources.
4. There are only two permissible locations for a sealed source; in use on the experiment or in the store.
5. Minimise manual handling of the source. Use remote handling.
6. Make sure there is a distance of more than 30cm and/or shielding between you and the source.
7. Report any loss or damage immediately to the demonstrator who will inform the RPS
8. Make sure the area you work in has been monitored for leakage by the RPS
9. If you are pregnant pay particular attention to the relevant section in the local rules, and notify a demonstrator.

[The RPS is Jayesh Hirani – Tel: 020 7594 7906 e-mail: j.hirani@imperial.ac.uk]